

THE AIR SPARGED HYDROCYCLONE FOR FINE COAL FLOTATION

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ABSTRACT

The cleaning of fine coal to achieve compliance specifications generally is a challenging problem for coal preparation engineers. Gravity separation techniques are limited with regard to capacity/efficiency considerations, and the most promising process alternative seems to be flotation, the use of which in the U.S. has grown significantly from an installed plant capacity of 47,000 tpd in 1965 to a plant capacity of 64,000 tpd in 1975 and a capacity of 145,100 tpd in 1985. Nevertheless, in all instances the efficiency of the flotation process for the production of a compliance coal product is limited by the liberation characteristics and the surface chemistry of the feed. Further, in a conventional flotation system, a relatively long retention time (>10 minutes) frequently is required to achieve acceptable separation efficiencies. In this regard, research and development efforts have shown that the most recent design of the high-capacity air-sparged hydrocyclone (ASH) can be used for the selective microbubble flotation of fine particles, and in view of these results further evaluation of the air-sparged hydrocyclone for the cleaning of fine coal is in progress.

Preliminary pilot-plant studies with a nominal 5-cm x 50-cm air-sparged hydrocyclone have been completed for a medium-volatile bituminous coal from Pennsylvania and a high-volatile bituminous coal from Alabama. In general, excellent separation efficiencies have been achieved using air-sparged hydrocyclone technology for microbubble flotation of coal with the results approaching a limit imposed by the washability characteristics of the feed. It is expected that clean coal products meeting compliance specifications can be made at high yields in the air-sparged hydrocyclone, provided sufficient liberation is achieved and an appropriate reagent schedule is established. Of equal or greater significance, however, is that the specific capacity of the air-sparged hydrocyclone appears to be as much as 500 times that of columns and conventional mechanical flotation cells.

INTRODUCTION

The importance of flotation technology in the mineral-processing industry continues to be of particular significance as evidenced by the U.S. flotation plant capacity for different commodity types presented in Table 1. Of all the commodities, coal has exhibited the greatest growth during the past decade. Coal flotation in the U.S. was first practiced in 1925 in the state of Wash-

Table 1. Flotation Plant Capacity in the United States

Commodity Type	Capacity (thousand tons/day)		
	1965	1975	1985
Sulfides	622	996	796
Industrial Minerals	191	467	527
Coal	47	64	145
Metallic Oxides	48	90	117
TOTAL	908	1617	1585

ington and in 1933 in Pennsylvania, but until recently was only of secondary importance in the production of steam coal. Frequently satisfactory ash and sulfur rejection cannot be obtained by gravity or heavy media concentration of plus 28 mesh coals; consequently, there is considerable potential to meet the market specifications on ash and sulfur by means of fine coal flotation. By the end of this century, with improved filtration techniques or the development of coal slurry technology, perhaps 10 million tpd of fine coal could be cleaned by froth flotation. Indeed, if we are to become coal exporters as some prognosticators foresee, such an expansion in the coal industry will be necessary. This calls for significant improvements in coal flotation technology. One area in which improvement may be possible is the area of flotation equipment innovations for increased productivity.

Flotation equipment development during the past decade has included the design, installation, and operation of larger mechanical flotation cells (aerated stirred tank reactors). In addition, considerable effort has been made during the past decade to develop column flotation technology in the U.S. and elsewhere, leading to a number of industrial installations. Nevertheless, for both mechanical and column cells the specific flotation capacity for coal is generally limited to 1-2 tpd per cubic foot of cell volume.

In contrast with conventional flotation equipment, it is expected that the air-sparged hydrocyclone (ASH) will have a specific flotation capacity for coal of at least 100 tpd per cubic foot of cell volume. In this regard, an extensive ASH test program has been planned by Penelec with support from DOE at the EPRI Coal Quality Development Center in Homer City, Pennsylvania (Chironis, 1987). After describing the features of microbubble flotation with the air-sparged hydrocyclone and discussing how this relates to fundamental aspects of flotation, preliminary results from pilot-plant studies on a medium-volatile bituminous coal from Pennsylvania and a high-volatile bituminous coal from Alabama with a nominal 5-cm x 50-cm ASH unit will be discussed with respect to design and operating variables.

FEATURES OF THE ASH SYSTEM

The air-sparged hydrocyclone was developed during the early 1980s in order to achieve fast flotation of fine particles in a centrifugal field (Miller, 1981, 1983a, 1983b). A schematic drawing of the air-sparged hydrocy-

clone is presented in Figure 1. Basically the air-sparged hydrocyclone consists of two concentric right-vertical tubes, a conventional cyclone header at the top, and a froth pedestal at the bottom. The inner tube is a porous tube through which air is sparged radially. The outer nonporous tube simply serves as an air jacket to provide for even distribution of air through the porous inner tube. The slurry is fed tangentially through the conventional cyclone header inside the porous tube to develop a swirl flow of a certain thickness in the radial direction (the swirl-layer thickness) and is discharged through the annular opening between the inner porous tube wall and the froth pedestal. Air is sparged through the jacketed, inner porous tube wall and is sheared into small bubbles by the swirl flow. Hydrophobic particles (coal) in the slurry collide with these bubbles and, after attachment, are transported radially into a froth phase which forms on the cyclone axis. The froth phase is stabilized and constrained by the froth pedestal at the underflow and thus moves towards the vortex finder of the cyclone header and is discharged as an overflow product. Hydrophilic particles (mineral matter) generally remain in the slurry phase and are discharged as an underflow product through the annulus created by the froth pedestal.

FUNDAMENTAL CONSIDERATIONS

Bubble/Particle Contact and Attachment

Froth flotation in any flotation machine is accomplished by attachment of hydrophobic particles to buoyant bubbles while hydrophilic gangue particles or particles with lower hydrophobicity are wetted by water and remain suspended in the slurry. The fundamental flotation step involves bubble/particle contact for a sufficient time to allow film rupture, and thus attachment is established. In this way, a contact time and an induction time are distinguished. The former is determined by bubble/particle motion and controlled by the hydrodynamics of the system. The latter is dominated by surface chemistry features of the bubble and the particles and can be altered by flotation reagents. Further, the former refers to the time during which a particle would be in contact with the bubble, while the latter is usually recognized as the time required for thinning the water film between the particle surface and the air bubble to such a thickness that rupture takes place.

The manner of bubble/particle contact has been studied theoretically by several investigators and includes sliding contact models (Sutherland, 1948; Dobby and Finch, 1986) and collision contact models (Evans, 1952; Ye and Miller, 1987a, 1987b). In the sliding models, bubble/particle contact is considered as an event during which the particle slides over the bubble surface as a result of their relative motion. In the collision models, the contact is considered as an event during which the particle collides with the bubble, causing the bubble surface to deform to the particle shape so that thinning of the water film is facilitated. The contact time in the former models relates largely to relative bubble/particle velocity and in the latter models is independent of such velocity but depends significantly on bubble mass, particle mass, and surface tension.

From high-speed video analysis of flow in a specially designed ASH system with plexiglass windows, it has been noted that bubbles acquire tangential and axial velocity components as they penetrate the swirl layer and enter the froth core as shown by the insert in Figure 1. Though these two velocities

AIR - SPARGED HYDROCYCLONE

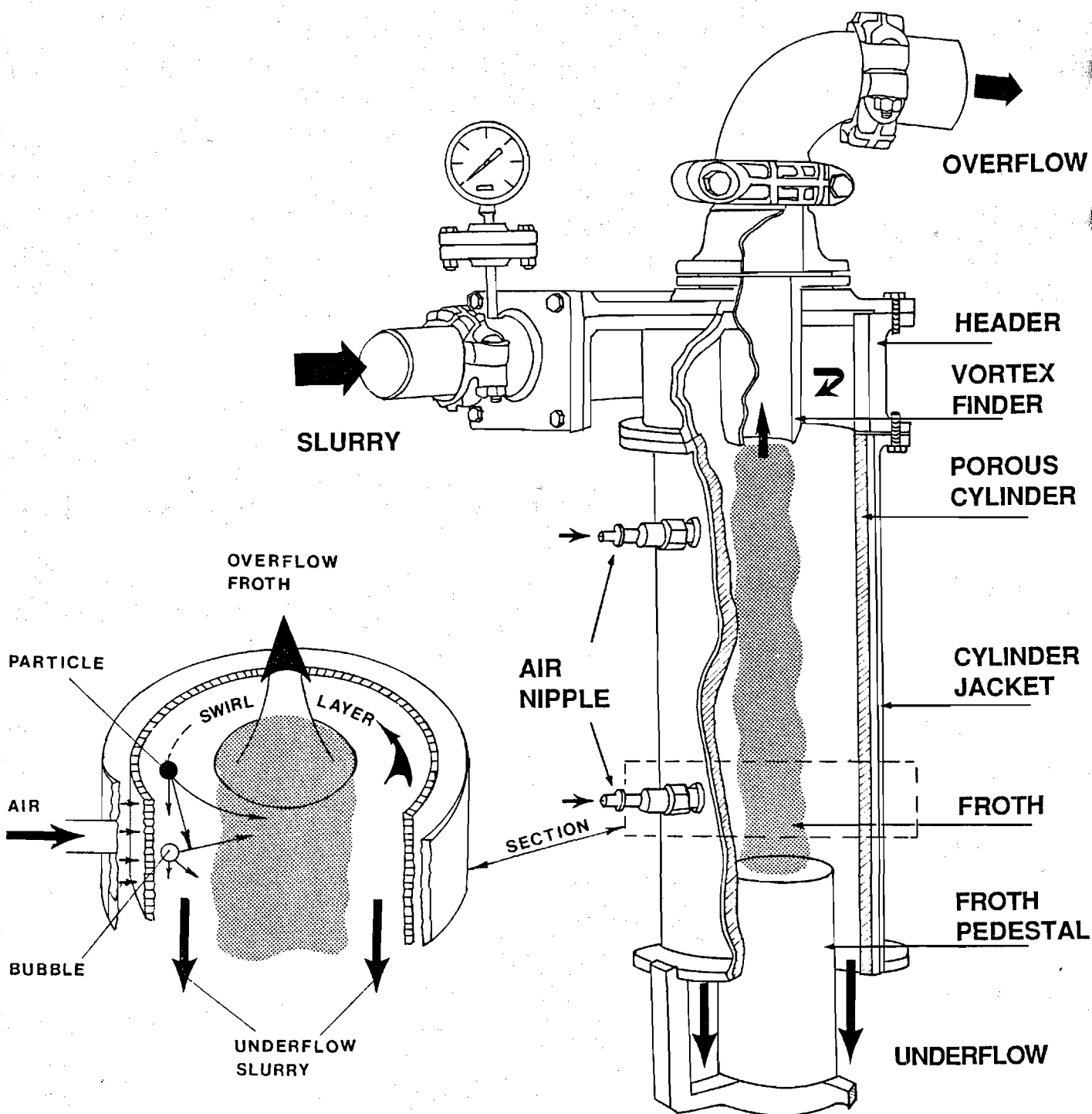


Figure 1. Perspective view of the air-sparged hydrocyclone, including flow characteristics.

are affected by air flow rate and slurry pressure (the latter controls tangential and axial velocities of the slurry in swirl motion), they are relatively small in comparison with the radial velocity of the bubbles. Thus, the motion features of bubble and particle in an air-sparged hydrocyclone can be simplified as a motion in which there is a right angle between the radial bubble velocity vector and the particle velocity vector (combination of tangential and axial vectors). In previous experiments, it has been shown that the tangential and axial velocity of the fluid in an air-sparged hydrocyclone vary with the axial distance from the cyclone roof; for a 5-cm ASH a tangential slurry velocity of at least 3 m/s is expected (Miller et al., 1985). With this velocity value and the motion features of bubble and particle in an ASH system as characterized above, contact times calculated by sliding models are orders of magnitude smaller than directly measured induction times of hydrophobic mineral particles, while collision models provide a contact time of the appropriate magnitude. From this point of view, it is suggested that in general, and for the ASH system in particular, bubble/particle attachment occurs by collision contact rather than by sliding contact.

Flotation Pattern

A simplified flotation pattern in the air-sparged hydrocyclone based on experimental observation is shown schematically in Figure 1. When slurry is fed tangentially through a conventional cyclone header into the porous tube a swirl flow of a certain thickness adjacent to the porous tube wall is developed, leaving an empty air core at the center of the tube. When air is sparged through the porous tube wall into the swirl layer, small air bubbles are formed. Hydrophobic particles in the slurry thus collide with these bubbles and, after attachment, are transported into the center of the cyclone. The air core becomes a froth core. Hydrophilic particles generally remain in the slurry phase, which is discharged as the swirl layer through the annular underflow opening between the porous tube wall and the froth pedestal. A pedestal supports the froth core which is continuously replenished, being axially transported to the vortex finder and discharged as an overflow froth product.

A pressure difference (Δp) between the froth pedestal and vortex finder outlet can be monitored and is the actual driving force to axially transport the froth phase. Further, for a well-behaved system, the grade of the hydrophobic particles as well as solids concentration by weight is the highest in the center of the froth core and decreases radially to the concentration in the slurry phase at a particular elevation in the air-sparged hydrocyclone. This is an important feature of the flotation pattern for an air-sparged hydrocyclone, which strongly affects flotation performance and is controlled by design and operating variables. Furthermore, previous experiments have shown that the ASH system actually operates under a restricted condition in which the annular opening is usually less than the swirl-layer thickness, so that the pressure difference necessary for axial transport of the froth is ensured.

Swirl-Layer Thickness/Froth Core

Actually, the term "swirl layer," which has long been used in describing air-sparged hydrocyclone flotation, is not very correct, since everything including the froth core inside an air-sparged hydrocyclone is in swirl motion, as observed from a special ASH unit which has plexiglass windows on the top, middle and bottom. The term "swirl layer" is used to specify a particular

layer of slurry which exists adjacent to the porous tube wall. The motion feature of this layer is that it has a net axial velocity toward the annular opening between the porous tube wall and the froth pedestal, as illustrated in Figure 1. Early experiments which were carried out with a nonporous transparent right-vertical tube of plexiglass with water suggested that the thickness of this layer is 8 to 12% of the tube radius. These experimental data closely match the values predicted from inviscid fluid-flow theory for swirl nozzles proposed by Taylor et al. and from momentum balance/continuity equations derived for the air-sparged hydrocyclone (Miller et al., 1985). Later experiments which were carried out on a complete air-sparged hydrocyclone suggested a similar value but indicated that it slightly increases with frother addition and increase of air flow rate, due to the stabilization of fine bubbles in this layer as well as any disturbance to the swirl motion that might be caused by these bubbles (Miller et al., 1988).

Between the swirl layer and froth core, there exists a transition region, so defined because its net velocity in the axial direction is considered to be either zero or in the same direction as the slurry phase. The former condition exists when the froth core is very large, leaving little space for the transition region (Case I). The latter exists when the froth core is relatively small (Case II), under which circumstances the air-sparged hydrocyclone works as if part of its volume, sometimes more than half, is filled with water (or slurry). This has been observed from both hold-up volume measurements (Baker et al., 1988) and, recent observations with a specially designed ASH unit which has several plexiglass windows. Nevertheless, in both cases the swirl-layer thickness remains the same.

In general the case of a large transition region and a small froth core is to be avoided for effective air-sparged hydrocyclone flotation separations. When a large overflow opening area is adopted, slurry in the transition region will be inadvertently transported into the overflow stream, causing poor flotation selectivity. Further, it is observed that, in addition to the swirl motion and the axial flow of the froth core, the axis of the froth core, when the core is relatively small, has a certain degree of circular motion (drift motion). The axial drift of the fluid seems to account for the inadvertent transport of slurry to the overflow stream and froth to the underflow stream.

The diameter of the froth core can be controlled with the addition of frother. When a certain quantity of frother is added, the froth core becomes large and the transition region diminishes such that the hold-up volume of slurry in an ASH unit decreases; this has been confirmed by water hold-up volume measurements in an ASH unit (Baker et al., 1988) and particularly by direct experimental observation through plexiglass windows of a specially designed ASH unit. Further, it is understandable that the particle surface chemistry has an effect on froth core diameter and stability. When the froth is stabilized by a high percentage of hydrophobic particles, the froth core is enlarged, and the transition region diminishes. The air flow rate also has a significant effect on the froth behavior, which is to be discussed elsewhere (Miller and Ye, 1988).

Bubble Size

A simple theoretical expression for the size of a bubble formed in swirl flow from a single capillary has been derived before (Miller et al. 1985).

This analysis suggests that the bubble size (r_b) will become independent of the capillary size (r_o) and depend only on the air flow rate and the tangential velocity of the liquid when the bubble size is significantly larger than the capillary size ($r_o/r_b \ll 1$).

Table 2 presents some experimental results on bubble formation from single capillaries in a plexiglass hydrocyclone (Miller and Ye, 1988). The experiments were recorded and analyzed with the SP 2000 high-speed video system (Spin Physics of Eastman Kodak) having a capability of 2000 frames per second in the full-frame mode and 12,000 frames per second in the split-frame mode. The tangential velocity of the water was controlled at 2.8 m/s. The capillary size was 640 micrometers. It can be noted from the data that the bubble diameter is comparable in size to the capillary diameter and does not change appreciably with air flowrate (or flow ratio). In this regard, the assumption that the bubble diameter will be equivalent to the capillary diameter may be the most useful estimate. It should be emphasized, however, that these estimation procedures are based on data for rather large bubble diameters. The utility of these estimation procedures for bubble generation from smaller capillaries ($<100 \mu\text{m}$) still requires experimental verification. Furthermore, it is clear from Table 2 that surface tension does not have a significant effect on bubble size under these conditions in an air-sparged hydrocyclone. Bubble size essentially remains constant as the level of MIBC addition is increased from zero to 120 ppm.

Table 2. Bubble Size Formed From a Single 640-micrometer Capillary in the Swirl Flow of a Hydrocyclone at Different MIBC Additions and Air Flow Rates (Tangential Velocity of Water 2.9 m/s).

MIBC Addition (ppm)	Air Flowrate ($\times 10^{-6} \text{ m}^3/\text{s}$)	Bubble Size (μm)
0	0.08	510
0	1.67	720
0	2.50	870
40	0.08	510
40	1.67	700
40	2.50	870
80	0.08	500
80	1.67	700
80	2.50	850
120	0.08	500
120	1.67	700
120	2.50	840

Although frother addition appears to have no effect on the size of bubbles formed in the air-sparged hydrocyclone, addition of frother is essential for air-sparged hydrocyclone flotation and, in fact, previous experiments

(5-cm diameter ASH systems) have shown that the frother level required for air-sparged hydrocyclone flotation is sometimes higher than that for conventional flotation machines. Basically, high bubble/froth stability and minimal bubble coalescence are essential requirements in air-sparged hydrocyclone flotation because of its unique fluid flow and flotation patterns. These two requirements are controlled to a large extent by addition of frothers. With increasing addition of frother, bubbles become stabilized and coalescence is reduced; the froth core thus formed on the axis of the cyclone significantly increases in size, and the transition layer is reduced to a minimum, as was directly observed from a specially designed cyclone unit with plexiglass windows. Transport of hydrophobic particles to the overflow opening from the froth core is improved, and the flotation recovery is increased.

Tangential velocity of the slurry in an air-sparged hydrocyclone changes with the distance from the cyclone roof, (Miller et al. 1985), and capillary pores of the porous tube are not uniform but rather have a certain pore size distribution. Air flow rate in each individual pore will be different from that in other pores at a fixed pressure. These features will definitely affect bubble size formed at the porous tube surface of a complete air-sparged hydrocyclone system. However, based on the notion that the bubble size does not differ too much from the capillary size when the ratio of air velocity through the capillary to tangential water velocity in the cyclone is in the range from 0.3 to 3, it would be expected that bubbles formed in the actual air-sparged hydrocyclone do not differ much in size from the pore sizes of the porous tube in which case bubbles as small as 10 microns might be expected (Miller, et al. 1985). The distribution of bubble sizes should follow the distribution of the pore sizes as is predicted from the fact that the ratio of air velocity in the pores to tangential water velocity in the actual ASH system is close to the values used in the experiments for single capillaries. Nevertheless, experimental verification has not been completed at this time due to the difficulties encountered in bubble size measurements in the actual ASH system. In terms of bubble stability, however, it might be reasoned that the limiting bubble size will approach the thickness of the boundary layer at the surface of the porous tube and/or the size of turbulent eddies in the system.

COAL FLOTATION

As mentioned previously froth flotation is a physicochemical separation process that depends on the attachment of air bubbles to the surfaces of hydrophobic particles. Other hydrophilic particles are wetted by the aqueous phase and will not attach to air bubbles. Thus the separation of coal particles from mineral matter particles occurs as dispersed air bubbles pass through a suspension of mixed particles (typically minus 28 mesh); the bubble/particle aggregates float to the surface and are collected as clean coal concentrate. The hydrophobic character of coal particles varies with rank, extent of liberation, and the state of surface alteration (Jin, Ye and Miller, 1987). Depending on the above-mentioned factors, various levels of conventional flotation reagents, such as molecular oils, are required to enhance the hydrophobic character of coal particles while the mineral matter particles remain hydrophilic. These neutral molecular oils such as kerosene or fuel oil are called promoters and are used to enhance the attachment of air bubbles at the coal surface by forming a thin coating over the air bubbles and/or particles to be floated. In coal flotation, frothers such as methyl isobutyl car-

binol (MIBC), terpinol, cresols, polyglycols, and some specially blended reagents such as those marketed by Sherex, Dow and Nalco are frequently used. The choice of these reagents and level of addition depends on the coal to be floated and the desired level of selectivity with respect to ash and sulfur.

Although such a reagent schedule is used for conventional coal flotation, production of deep-cleaned coal by froth flotation can be difficult. It is important to note that, in order to produce a high-quality coal product, free of mineral matter and sulfur, the feed may have to be ground to fine sizes (minus 400 mesh). Under these circumstances several problems arise. The fine coal, due to its high surface area, adsorbs significant amounts of promoter and frother. The promoter which is used to increase the hydrophobicity of the coal particles inadvertently adsorbs on the mineral matter particles, and these particles subsequently report to the clean coal product, decreasing the quality of the product. The liberated fine mineral matter sometimes attaches to the hydrophobic coal particle (slime coating), resulting in a pseudodepression phenomenon. As a result of these considerations, the production of superclean or even compliance coal by conventional froth flotation methods has been a difficult task.

Another problem of conventional coal flotation has been sulfur rejection. With increasing demand on environmental control, the sulfur content in clean coal products (including organic and inorganic sulfur) has to be reduced to a minimum, especially because of our concern for the environment -- the need to contend with the acid-rain problem.

Prior art coal-flotation chemistry has been limited to the use of conventional frothers, oils, dispersants, depressants and alterations of these reagents in an attempt to gain some advantage in the separation of coal from mineral matter (including pyritic sulfur). Only modest success has been achieved. However, recent studies indicate that a new generation of coal flotation reagents may allow for improved pyrite and mineral matter rejection by chemical modification (Miller and Ye, 1987).

Improved pyrite and mineral matter rejection also may be possible by microbubble flotation with the high capacity air-sparged hydrocyclone. Since the initial work with the ASH in this area of coal flotation (Miller and Van Camp, 1982) subsequent research has led to significant improvements in the ASH technology and more recent results further demonstrate the potential of the air-sparged hydrocyclone for fine coal flotation.

General Features

Important features of coal flotation with the air-sparged hydrocyclone are; the level of hydrophobicity of the coal particles, froth stability (adjustment of oil and frother addition), low feed solids concentration (5% by weight), high proportion of hydrophobic coal particles (sometimes more than 80% of the feed solids must be transported into the overflow stream), and fine hydrophilic mineral-matter particles that are completely dispersed in the slurry.

Under these circumstances, high air flow rate is generally preferred. Slurry pressure should be controlled at a modest level because increasing slurry pressure does not bring about a great advantage for rejecting mineral-

matter particles (due to their small size) but rather causes poor flotation yield of coarse coal particles (28 x 48 mesh). For a given level of hydrophobicity and froth stability, the optimal slurry pressure is established by the relative proportion of coarse coal to fine clay or other mineral matter particles. Due to the fact that fine mineral-matter particles are dispersed in the slurry, water split into the overflow stream (froth) should be controlled at a minimum. This can be done by using the proper ratio of overflow opening area to underflow opening area at an appropriate air flow rate. Further, although a high solid split is encountered in coal flotation, volume split from feed to overflow stream in coal flotation usually is low because of low solids concentration used in coal flotation, and a relatively small overflow opening area is recommended to minimize transport of fine mineral-matter particles to the the overflow stream (together with the transport of water).

Performance Characteristics

With these strategic controls, coal cleaning with an air-sparged hydrocyclone gives a clean coal product quality comparable to or better than that achieved with conventional flotation equipment. In one case, a preliminary ASH test program on minus 100-mesh medium-volatile bituminous coal taken from a classifying cyclone overflow product (18% ash and 1.1% total sulfur) at a preparation plant in Pennsylvania showed promising results. Analysis of the feed material with respect to particle size showed that 60% of the mass, 86% of the ash, 65% of the total sulfur, and 80% of the pyritic sulfur occurred in the minus 400-mesh size fraction. A series of tests were carried out during which the performance of the air-sparged hydrocyclone unit was evaluated. A nominal 5-cm diameter x 50-cm long unit was used which could process coal at rates as high as 0.5 tph. The influence of both design variables (froth pedestal, length, pore size, vortex finder diameter) and operating variables (feed rate, air flow, reagent dosage, pulp density, conditioning time) on the performance of the air-sparged hydrocyclone was examined. Typical results from single-stage rougher flotation with a retention time of less than one second produced clean coal products containing 7 to 8% ash at yields of 70 to 80%, corresponding to an overall ash rejection of 70 to 75%. See Table 3. Detailed analysis of the products indicated that the minus 400-mesh material could be cleaned quite efficiently with a typical ash rejection of 70%. For example, the ash content of the minus 400-mesh fraction was reduced from 22.6% in the feed to 9.4% in the clean coal product for a single-stage rougher flotation step with a retention time of less than one second.

Table 3. ASH (5-cm x 50-cm) Flotation of Medium-Volatile Bituminous Coal from Pennsylvania. Feed material minus 100 mesh (>50% minus 400 mesh). Feed rate dry solids = 0.5 tph.

	wt %	% Ash	Distribution %	
			Ash	Coal
Clean Coal	72	6.5	27	82
Reject	28	46.9	73	18
Feed	100	17.8	100	100

Another series of air-sparged hydrocyclone tests was carried out on a high-volatile bituminous coal from Alabama. Samples of this material exhibit a considerably coarser particle size distribution. This high-volatile bituminous coal from an Alabama preparation plant had a top size of 28-mesh with 55% greater than 100-mesh. These typical flotation feed samples contained 11.5% ash. The influence of various parameters such as reagent levels, air flow rate, and slurry pressure were investigated. Of most significance, in the case of the high-volatile bituminous coal, was the effect of feed slurry pressure on the overall flotation recovery. For example, it has been demonstrated that the upper particle size flotation limit for an air-sparged hydrocyclone is strongly affected by the hydrophobic character of the particle itself (Miller and Ye, 1988) and is extended as the hydrophobicity of the particles increase. Further, the upper particle size flotation limit is adversely affected by feed slurry pressure which controls the tangential velocity of the slurry in swirl motion. These generalizations are demonstrated again from the size-by-size flotation recovery of coal particles shown in Figure 2. Flotation recovery of 200- μm coal particles is decreased from 70% to 15% as the slurry pressure increases from 5 psig to 20 psig at a constant kerosene addition of 0.5kg/ton. The decrease in the flotation recovery is due to the increased centrifugal force acting on particles at higher slurry pressure which prevents stable bubble/particle attachment. When a high kerosene addition is used (1.5 kg/ton) to improve the hydrophobic character of the coal, the flotation recovery of the 200- μm coal particles is restored to some extent increasing from 15% to 50%. A typical separation under preferred operating conditions resulted in a clean coal product having an ash content of 5.5% at a yield of 65 to 70% as shown in Table 4.

Table 4. ASH (5-cm x 50-cm) Flotation of High-Volatile Bituminous Coal from Alabama. Feed material minus 28 mesh (>50% plus 100 mesh). Feed rate dry solids = 0.5 tph.

	wt %	% Ash	Distribution %	
			Ash	Coal
Clean Coal	67.2	5.7	45	55
Reject	32.8	13.2	55	45
Feed	100	7.9	100	100

In general, excellent separation efficiencies have been achieved by air-sparged hydrocyclone flotation with the results approaching a limit imposed by the washability characteristics of the feed. Figure 3 presents the ash content versus yield with different flotation techniques for the medium-volatile bituminous coal from Pennsylvania. The bench-scale test was performed with a two-liter flotation cell, while the air-sparged hydrocyclone test was done with a nominal 5-cm x 50-cm ASH system at a specific dry solids feed capacity of 100 to 150 tpd/ft³ of cell volume.

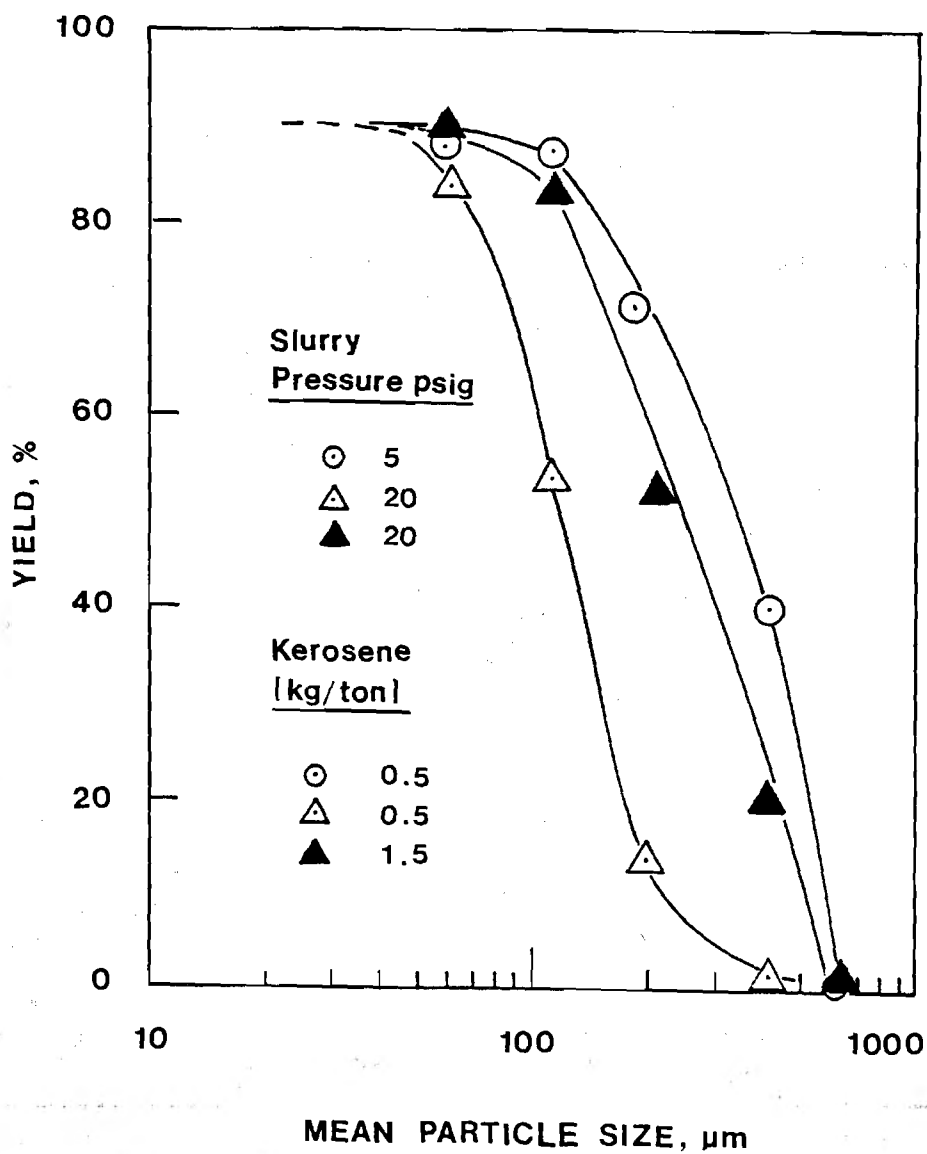


Figure 2. Size-by-size flotation recovery of Alabama coal (high-volatile bituminous) for two different slurry pressures and two different levels of reagent addition (Ye et al., 1988).

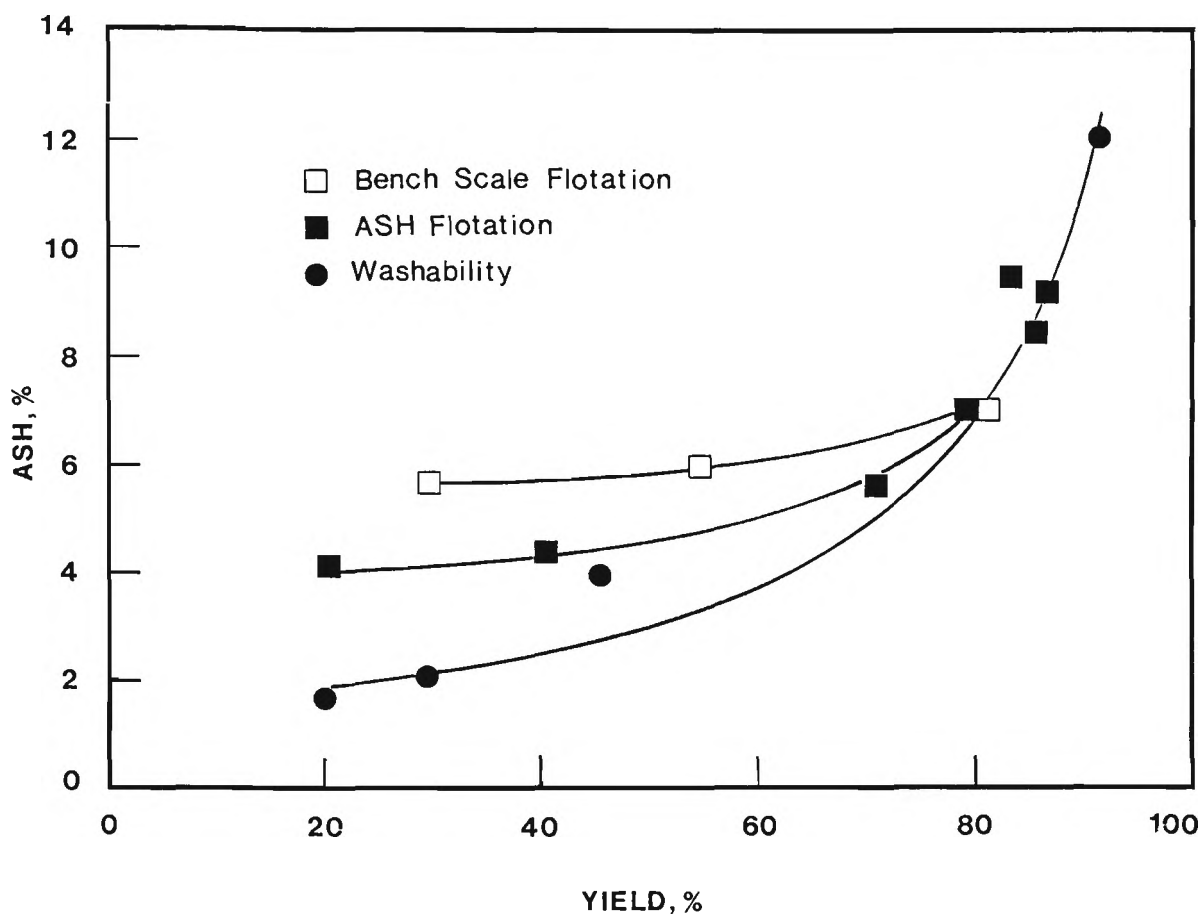


Figure 3. Flotation behavior of medium-volatile bituminous coal compared to washability characteristics.

SUMMARY AND CONCLUSIONS

Research and development efforts are being continued to determine preferred design features and scale-up criteria for air-sparged hydrocyclone flotation. It is expected that clean coal products meeting compliance specifications can be made at high yields in the air-sparged hydrocyclone provided sufficient liberation is achieved and an appropriate reagent schedule is established. Of particular significance however, is that the specific capacity of the air-sparged hydrocyclone appears to be as much as 500 times that of columns and conventional mechanical flotation cells.

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